3. Sea-Level Rise

3.1 INTRODUCTION

Most researchers agree that sea level is currently rising and has been since the end of the last ice age about 17,000 years ago (Scientific American August 1998). The evidence for rising sea levels comes from direct measurements of the ocean water column, the geologic record, changes in the earth's angular momentum, and melting glaciers. Thermal expansion of ocean water due to increased surface warming and an increased water supply from glacial melt are the two main causes of increased sea level.

Tectonic sinking and human-induced sinking of the ground (for example, by hydrocarbon extraction, ground water pumping, or settlement of Delta levees) also may cause relative sea-level rise. When combined with rising sea levels due to climatic and oceanic factors, a total sea-level rise may be obtained for any given area where measurements are available.

Only the long-term rise in sea levels due to fresh-water influx from melting glaciers and oceanic thermal expansion factors are considered here. Site-specific amounts of total sea-level rise may be calculated as needed and are beyond the scope of this work.

Since near the beginning of this century, the rate of sea-level rise has been from about 1 to 3 millimeters per year (mm/yr). If the sea level continues to rise at the present rate, low-lying beaches, wetlands, and critical infrastructure such as levees will become further inundated and threatened by increased water surface levels, wave erosion, and associated problems. Since much of the Bay-Delta system is at or near sea level, it is likely to be directly affected by rising sea levels. Levee height determinations may need to be increased to prevent levee overtopping and subsequent levee failure.

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3.2 ATMOSPHERIC WARMING AND SEA-LEVEL RISE

One of the major causes of rising sea levels is an increase in atmospheric temperatures. Increasing atmospheric temperatures heat ocean waters and cause them to rise by thermal expansion. Warmer temperatures also are responsible for the increase in melting of terrestrial and oceanic glaciers. Average atmospheric temperatures have risen about 1 degree Fahrenheit (0.6 degree Celsius) since the turn of the century (Titus and Narayanan, EPA 1996). Warming trends are not the same on all continents and in all oceans, but rather are

an average of global climate trends. Local climates may actually be cooling, as discussed by the National Oceanic and Atmospheric Agency (NOAA) at **http://www.ncdc.noaa.gov/ol/climate/globalwarming.html#Q1**. Many climate experts believe that the overall warming trend is a result of an increase of anthropogenic carbon dioxide and other so-called "greenhouse gasses."

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There is considerable debate on the effects of greenhouse gases. For example, Curt Suplee at **http://www.Globalwarming.org** reports that increases in carbon dioxide concentrations may actually follow warming trends. However, the uncertainty of the cause of warming is high, and much more research is needed to resolve the issue. While earth-based instruments show a distinct warming trend, space-based measurements of atmospheric temperatures over the past decade or so show no such trend and instead show a small cooling trend in some cases. However, it is also possible that the climate system does not react instantly to increases in greenhouse gases. The effects of the input of such gases to the atmosphere may not be linear and possibly may not be felt until a future time. This view is detailed at **http://www.artsci.wustl.edu/~rjniemie/hewterm.html.**

Research into atmospheric warming is continuing. Instruments such as those aboard the currently planned CloudSat satellite will better enable scientists to determine whether the atmosphere is getting warmer (Space News May 1999).

3.2.1 MELTING GLACIERS AND SEA-LEVEL RISE

Besides thermal warming of ocean waters, the other major input to sea-level rise is glacial melt water. While no glaciers are present in the project area and no volumes have been estimated, relatively rapidly melting glaciers are a current phenomena in many other places. Terrestrial glaciers are melting at a seemingly accelerated pace throughout the world. The web sites referencing this melting are:

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- **http://www.tv.cbc.ca/national/pgminfo/glacier/index.html** shows photographs of the retreating Athabascan Glacier.
- **http://www.enn.com/enn-news-archive/1998/05/052798/glacier.asp** gives a discussion of the melting of glaciers at various locations.
- **http://www.greenpeace.org/~climate/database/records/zgpz0212.html** shows the amount of glacial retreat at various locations.
- **http://spacelink.nasa.gov/NASA.News/NASA.News.Releases/Previous.News.Releases/99.News.Releases/99-03.News.Releases/99-03-04.Greenland.Glaciers.Shrinking** reports the unexpected recent change in the Greenland Ice Sheet.

Continued measurements over the next decade will expand the amount of factual information concerning glacial melting. This would be especially important in the case of a possible breakup and melting of very large glaciers, for example, on Greenland or in the Antarctic ice system.

The April 1999 Scientific American reports that the glaciers of Glacier National Park in Montana will run dry within the next 50 years. For comparison, about 6% of the world's ice is contained in mountain glaciers. The Antarctica and Greenland Ice Sheets contain about

90% of the world's fresh water. Melting of the ice sheets could sharply accelerate sea-level rise. Photographs showing the breakup of the Larsen Ice Shelf in the Antarctic can be found at **http://www-nsidc.colorado.edu/NSIDC/ICESHELVES/ lars_wilk_news**. The rapid retreat of summer sea ice in the Beaufort Sea north of Alaska is detailed in the February 1999 Science News.

3.2.2 MEASURING THE AMOUNT OF SEA-LEVEL RISE

Measuring sea-level rise is complex. Seaborne measurements over the last 100-150 years indicate that globally, the sea level has been rising at the rate of about 2 mm/yr. This amount will vary with location. The global average from tide gage records (Gornitz 1994) is from about 1 to 3 mm/yr.

Tide gages provide the most direct measurements of sea-level rise; however, tide gages usually are placed on piers near a geodetic benchmark. Some serious problems are associated with tide gage measurements. Local movements caused by postglacial rebound or subsidence greatly modifies the rate of relative sea-level rise or lowering, as may be the case. Tide gages also must be resurveyed periodically to correct for changes in gage platform mountings. The length of record is important, with 50 years of record probably being the minimum length for accurate measures. A detailed discussion of tide gage measurement accuracy can be found at **http://www.agu.org/revgeophys/dougla01/node3.html#SECTION00030000000000000000**.

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Modern electronic measurements such as GPS- (global position system-) based measures, and laser and satellite altimetry offer the most consistent and accurate methods available to measure sea-level fluctuations. Problems with these techniques can occur from various kinds of instrument noise and interference, but they can be resolved. Over time, these techniques will provide very accurate measures of sea surface changes. Since electronic techniques are relatively new, they do not offer the history of measurements provided by tide gage data. Nevertheless, when combined with computer models over the next decade, the measurements should provide good baseline sea-level data and better insight to sea-level changes over time.

Plans now call for launching a series of earth observation system (EOS) observatories. LandSat 7 was launched in April 1999, with more instruments scheduled to be placed in orbit steadily through 1999 and the coming years. European Space Agency and Japanese platforms also will be launched. Measurements will extend beyond the first decade of the 21st century, providing 10- to 15-year data sets. Scientists believe they can obtain important insights into how the earth system collectively works and provide a quantitative basis for 10- to 100-year predictions of global change. See NASA Facts Online at **http://pao.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/earthsci/eosund.htm** for discussion. Mission descriptions and launch schedules may be linked at **http://www.earth.nasa.gov/missions/index.html**.

Current space-based projections of short-term sea levels have been made with some accuracy in the case of the 1997 El Niño and 1998 La Niña events. The TOPEX-Poseiden home page at **http://topex-www.jpl.nasa.gov** links to color plots of sea-level heights determined from satellite altimetry.

Not all researchers agree on the amount that sea level might rise over a given time span or in a geographic location. For this report, a survey was made of nine current sea-level rise projections. The average of these projections shows that the global sea level could rise about 3.4 inches over the next 50 years, not including additional rise caused by increased warming. (If the sea level continued to rise at the rate of about 1.8 mm/yr for the next 50 years, by 2050 the ocean would have risen on average 3.4 inches.) This rate of sea-level rise is close to historical average rates of rise and varies with location.

The average rate above does not include a possible increased rate of rise due to increased climate warming and resultant thermal expansion. The trend of warming and sea-level rise is predicted by many to be non-linear in the next century. When increased rates of warming are included, the average of surveyed projections of sea-level rise shows that global sea level could rise 7.2 inches by 2050 and 17.2 inches by 2100.

Predictions of sea-level rise are based on historical data, satellite and GPS measurements, seaborne measures, and mathematical models. It is important to note that future trends in sea-level rise may not be linear. Sea-level observations and models are being calibrated as techniques and technologies improve over time. The U.S. Environmental Protection Agency (EPA) is at the forefront of research on global warming and sea-level rise. The EPA has included recent global warming projections in their model; results show that by 2050, global sea levels might be expected to rise 5.9 inches. The same models show that by 2100, sea levels might rise by about 13.4 inches. These results may be viewed at **http://www.epa.gov/docs/oppeoee1/globalwarming/reports/pubs/sealevel/probofsea/index.html#toc**.

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3.2.3 EFFECTS ON THE BAY-DELTA SYSTEM

Ground elevations in the Bay-Delta system vary from at or near sea level in the San Francisco Bay area to 10 feet and more in the Sacramento area. The effects of a rising sea level on inland areas will be in direct proportion to the amount of ocean rise. Effects will scale down to very little in the far northeast and southeast reaches of the Delta, where tide effects are diminished along with increasing river and waterway elevations.

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Climate warming does not appear to be occurring as fast as predicted in the late 1980s and early 1990s. In 1996, the EPA published "The Probability of Sea Level Rise," which lowered the climatic warming projections and published a set of tables to be used in the projection of sea-level rise numbers at various locations in the coastal United States. The average rate of rise for the San Francisco Bay Area is given as 1.3 mm/yr. This average alone would result in a rate of rise of 2.6 inches in 50 years. An additional component of sea-level rise due to increased warming is given as 3.9 inches (10 cm) by 2050. Combining these terms gives a total projected EPA sea-level rise of 6.5 inches by 2050 for the San Francisco Bay Area. The EPA method is found at **http://www.epa.gov/docs/oppeoee1/globalwarming/reports/pubs/sealevel/probofsea/Chpt9.pdf**.

This projection is for the average trend and warming only, and does not contain a component for the addition of water from melting glaciers. The EPA report does contain discussion and diagnosis-level quantities for a Greenland contribution.

Other agencies in the Bay-Delta area have considered the possible effects of sea-level rise. For example, the Bay Area Conservation and Development Commission (BCDC) in 1987

commissioned the report, "Sea Level Rise Predictions and Implications for San Francisco Bay."

The report is detailed and provides total sea-level rise projections for 2006 and 2036. Sea-level rise projections due to thermal expansion were based on a 1.8-mm/yr average taken linearly over the period of interest. This Bay Area rate was higher than the century-long average global sea-level rise of 1.2-mm/yr cited in the report. For comparison, the EPA uses 1.3 mm/yr for the Bay Area, not including the warming component. The BCDC used only average rates and did not consider a warming component in its projections, relying on a long period of record at the Presidio gage.

Based on a continuous record since 1855 at the Presidio, the rate of rise was 0.0039 ft/yr, or 1.2 mm/yr. During the most recent 19-year tide period (1967-1985), the rate was estimated at 0.0072 ft/yr, or 1.8 mm/yr. The greater rate in this period of measure was in part caused by inclusion of the 1983 El Niño event. Even without the El Niño component, however, the rate was 0.0059 ft/yr, or 1.5 mm/yr. The rate of sea-level rise appears to be increasing over time. These rates give a projected 3.5-inch rise over a 50-year period with no El Niño component, and a 4.3-inch rise over 50 years including the El Niño component. The rate with the El Niño component was used as a working average in the BCDC report. Table 9 compares the rates discussed.

Considering the projections of sea-level rise in Table 9, it is estimated that sea level will rise from 3 to 6 inches near the Golden Gate Bridge by 2050. Using the upper end of this range, the effects on the Bay-Delta system might range from 6 inches of increased water surface elevation near the Golden Gate Bridge, to 4 inches of rise in the area of Venice Island in the mid-Delta, to no rise at the "H" Street Bridge in Sacramento. Again, these figures are based on the upper end of the range, or 6 inches of rise by 2050 near the Golden Gate Bridge. If the lower end of the range is assumed (3 inches of rise by 2050 near the Golden Gate Bridge), these projections would be half at all locations. The far right column of Table 10 shows the estimated upper end of the projected sea-level rise by location.

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3.2.4 EFFECTS ON DELTA LEVEES

Projected sea-level changes must be considered in meeting the PL 84-99 levee standard.

A major goal of the Long-Term Levee Protection Plan is to reconstruct and maintain all Delta levees to the PL 84-99 standard. This standard is based on the Corps' Delta-specific 100-year flood elevation. This standard is affected by the elevation of sea level. If this goal is to be achieved, therefore, projected sea-level changes must be considered.

Table 10 shows changes in the amount of projected sea-level rise with tide gage location.

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3.3 CONCLUSIONS AND RECOMMENDATIONS

Local land settlement, expansion of ocean water, and the addition of water through glacial melting cause sea levels to rise. Increased atmospheric temperatures, measured over the past century, are causing thermal expansion of ocean water. Although glaciers are melting and

Table 9. Amount of Projected Sea-Level Rise: A Comparison of Historical Average and Projected Increased Warming-Induced Sea-Level Rise Components and Totals

Location and Component of Projection	Average Rate/Year (mm)	Number of Years	Average Rise Component	Projected Warming Component	Sea-Level Rise (mm)	Sea-Level Rise (inches)
Bay Area						
EPA historical average	1.3	50	65	0	65	2.6
EPA projected warming component	-	50	0	100	100	3.9
EPA average + warming component	-	50	65	165	165	6.5
BCDC historical average	2.2	50	109	0	109	4.3
Global						
Other agencies historical average	1.8	50	88	0	88	3.4
Other agencies average + warming component	-	50	-	-	183	7.2
Other agencies average + warming component	-	100	-	-	437	17.2
EPA average + warming component	-	100	-	-	340	13.4

Notes:

Various other investigative agencies report different amounts of sea-level rise. The amounts have been averaged. EPA amounts are lower than other agency amounts due to decreased amounts of projected global warming.

BCDC = Bay Area Conservation and Development Commission
EPA = U.S. Environmental Protection Agency
mm = millimeters

receding worldwide, the contribution of glacial-melt water to sea-level rise has not been well quantified. The increase in temperatures has not been conclusively linked to the increase in anthropogenic greenhouse gases. The research into global greenhouse warming is continuing. Current measures and computer models already have lowered warming projections made in the late 1980s and early 1990s.

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The methods used to measure sea-level rise have traditionally been land-based. As more space-based instruments are used in the coming decade, the accuracy of sea-level measurements will increase. A series of sophisticated space-based instruments soon will be placed into orbit for the purpose of measuring and understanding the complex interactions of the climate systems of the earth. Understanding these systems will have a direct bearing on civil works programs such as the Levee System Integrity Program Plan.

Table 10. Amount of Projected Sea-Level Rise at Bay Area and Delta Tide Gage Stations

Tide Gage Station Location	Approximate Daily Tide Fluctuation (feet)	Tide Decrease Factor	Adjusted Sea-Level Rise (feet)	Adjusted Sea-Level Rise (Estimated Upper End) (inches)
Golden Gate	5.8	1.1	0.5	6
Martinez	5.6	1.0	0.5	6
Rio Vista	4.8	0.9	0.4	5
Roaring River	4.4	0.8	0.4	5
Mallard Island	5.1	0.9	0.5	6
Antioch	4.3	0.8	0.4	5
Tracy	3.0	0.5	0.3	3
Venice Island	3.8	0.7	0.3	4
Freeport	1.7	0.3	0.2	2
Thornton	1.5	0.3	0.1	2
"I" Street Bridge	1.1	0.2	0.1	1
"H" Street Bridge	0.0	0.0	0.0	0

It is recommended that a 3- to 6-inch sea-level rise be assumed for a 50-year planning horizon for the San Francisco Bay Area. The assumed sea-level rise will decrease to 0 in the far northeast and southeast reaches (see Table 10) of the Delta, where tide effects are eliminated by increasing river and waterway elevations. For comparison, the Corps' New Orleans District (Britsch, personal communication May 1999) is using about 6 inches per year for projected sea-level rise due to thermal expansion. As more accurate sea-level rise projections become available, CALFED will make adjustments accordingly.

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